GOPEX: A Deep-Space Optical Communications Demonstration With the Galileo Spacecraft

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An Earth-based Galileo optical communications Xmtr (GOPEX) demonstration is the first attempt to demonstrate deep-space optical communications with a spacecraft during flight. The optical transmitter consists of a Nd:YAG laser integrated with the 24-in. telescope located at the Table Mountain Observatory (TMO). The receiver is a solid-state imaging camera on board Galileo. The primary objectives of the demonstration are to better understand the issues involved in blind-pointing to a spacecraft traveling in deep space and to assess the quality of the optical uplink by comparing the results of this experiment with theoretical predictions. The demonstration is scheduled for December 1990 and December 1992 during the Earth-encounter phases of the Galileo trajectory.

I. Introduction

Optical communications is a technology that offers a substantial increase in link capacity for the return of space-acquired data over conventional radio-frequency communications systems. This technology also provides reductions in size, weight, and power on the spacecraft. This increased capacity is especially important in realizing the goals of the proposed Space Exploration Initiative (SEI). A coordinated plan for the development and demonstration of optical communications for deep space has been prepared and documented elsewhere in this volume [1]. The plan was developed in concert with the Telecommunications and Data Acquisition (TDA) and the Technology and Applications Program (TAP) offices and is based on the Jet Propulsion Laboratory's (JPL's) 10 years of technology development and systems planning experience in this area. The plan includes component technology developments, future systems planning, and a set of representative systems-level demonstrations. One of the early activities is the demonstration of Galileo optical communications from an Earth-based Xmtr (GOPEX).

The GOPEX demonstration was conceived as a low-cost, early-on demonstration that would identify any uplink optical pointing problems and verify optical communications link-performance prediction models. The demonstration would utilize the imaging camera on the Galileo spacecraft (while the spacecraft is in close proximity with the Earth during the Earth gravity-assist phases) as an optical communications receiver to detect pulsed-laser signals sent from a telescope at JPL's Table Mountain Observatory (TMO).

This article describes the GOPEX program. Section II gives a technical description of GOPEX, which includes the objectives of the two gravity-assist phase demonstrations as well as the two precursor demonstrations using Earth-orbiting satellites. Preliminary link feasibility analyses are also presented. In Section III the activities that must be completed in preparation for the demonstrations are discussed, followed by a description of the coordination activities that are in progress with the Galileo Project and that will be necessary to obtain formal concurrence from the project to perform the demonstrations. In Section V some of the technical challenges of GOPEX are highlighted, followed by conclusions in Section VI.

II. Description of GOPEX

A. The Demonstration

The GOPEX demonstration represents the first attempt at optical communications with a spacecraft in flight. The demonstration is scheduled for the Earth-flyby periods of Galileo's VEEGA (Venus–Earth–Earth gravity assist) trajectory in December 1990 and December 1992 (see Fig. 1). During these flybys, the attitude heading of the spacecraft is such that prior to the first Earth gravity assist (EGA1), the sunshield on Galileo obscures the Earth from the field of view of the solid-state imaging (SSI) camera [2] until shortly before closest approach. However, when the Earth is unobscured, TMO is not one of the Earth features that is within the field of view of the camera until after closest approach. For the second Earth gravity assist (EGA2), the sunshield again obscures the Earth from the SSI camera for at least 70 days prior to Earth's encounter. Thus, the spacecraft's attitude headings prior to both Earth encounters effectively preclude pre-encounter optical communications demonstrations. However, after closest approach, the Earth is visible to the SSI camera on both flybys, providing opportunities for the GOPEX demonstration.

The basic concept of the GOPEX demonstration is to transmit a laser beam to Galileo from a ground-based telescope (Fig. 2). The laser beam is intensity modulated (on-off) by a data sequence that will be transmitted. If the Galileo SSI camera had a higher speed photometer, the received optical signal could be detected and demodulated directly. Unfortunately, the framing rate of the SSI is too slow to accomplish this. However, if the laser signal originates from a dark portion of the Earth, and if during the time of transmission the spacecraft camera is scanned across the Earth in a direction parallel to the Earth-illumination terminator while keeping its shutter open, the temporally modulated laser signal will be focused on a moving path across the charge-coupled device (CCD) detector located in the focal plane of the camera. In this way, a single camera image can record an entire sequence of uplink laser pulses (Fig. 3). The image is then relayed to the ground for analysis using the spacecraft's X-band (8.5-GHz) transmitter. By examining the sequence pattern on the image, as well as the intensity levels of the image pixels, the uplink optical communications link can be evaluated.

The optical transmitter for the uplink to Galileo consists of a Q-switched Nd:YAG laser coupled to the 24-in. astronomical telescope at TMO. The SSI camera on board Galileo is the optical receiver at the spacecraft. The GOPEX laser operates at both the 1.06-μm fundamental frequency and at the 0.532-μm doubled frequency, emitting 10-nsec-wide Q-switched pulses at a maximum repetition rate of 30 Hz. The output energy per pulse from the laser is 750 mJ at the fundamental wavelength of 1.06 μm and 250 mJ at the 0.532-μm frequency-doubled wavelength (green). The SSI camera receiver consists of an 800-by-800 line element CCD detector array at the focal plane of an f/8.5 Cassegrain telescope of 1.5-m focal length [3]. The transmission of the camera optics is approximately 50 percent from 0.4 μm to 1.1 μm, and the angular resolution of the CCD is 10.6 μrad per pixel. The laser pulse, therefore, will appear as a bright spot on a single pixel in a camera frame.

Although the spacecraft returns to Earth for gravity assist twice (in December 1990 and December 1992), the geometries of the flybys are such that during EGA1, the laser will predominantly be in a solar-illuminated portion of the Earth and the spacecraft will appear low in the sky as seen from TMO. Therefore, a best efforts demonstration with reduced objectives will be performed at that time. During the second gravity-assist period, the viewing illumination geometries are much more favorable, permitting the full GOPEX objectives to be realized.

B. Objectives of EGA1 and EGA2

As mentioned earlier, the spacecraft attitude precludes camera viewing of the Earth during the EGA periods until after Earth closest approach (ECA). (The two GOPEX demonstration windows will be referred to as post-ECA1 and post-ECA2.)

During the post-ECA1 period, the Sun–Earth–spacecraft angle is approximately 40 deg, and the Earth as viewed from the spacecraft is a bright orb with a thin dark crescent. Conversely, the spacecraft is only visible from TMO during the daytime, rising to a maximum elevation of 20 deg above the horizon at noon. The laser signal will be contrasted against a bright Earth background and must be identified in an Earth scene consisting of the albedo variations of a winter sky. The low elevation of Galileo in the sky and the bright Earth background are conditions that exacerbate the effects of refraction and poor signal-to-background contrast. Consequently, the objectives of the EGA1 demonstration have been descoped from those of a full-up optical communications demonstration. The objectives of the EGA1 are

(1) To demonstrate blind-pointing capabilities of the uplink laser using spacecraft ephemeris predictions and available guide stars.

(2) To shake down the laser communications transmit equipment.

(Note that during the EGA1 demonstration, the camera will not be scanned over the Earth.)

Galileo's trajectory during the post-encounter period of the 1992 Earth flyby allows for a full-up optical communications demonstration at both the 0.532-μm and 1.06-μm wavelengths. Here, the Sun–Earth–spacecraft angle is approximately 90 deg, and Galileo rises to approximately 50 deg above the horizon in the early morning hours. The SSI camera thus "sees" TMO against a dark Earth background, resulting in excellent signal-to-background contrast. The objectives of the 1992 EGA2 GOPEX demonstration are

(1) To verify the uplink pointing capabilities over longer distances than demonstrated during the first Earth flyby (30 million km instead of 4 million km).

(2) To demonstrate the acquisition of the temporally modulated optical signal by scanning the SSI camera across the Earth image.

(3) To evaluate optical uplink performance at both the 0.532-μm and 1.06-μm wavelengths.

(4) To verify theoretical optical telecommunications performance predictions.

During the EGA1 Galileo flyby, the uplink laser will emit a 10-nsec pulse every 6 min. Due to the brightness of the earthshine background, the camera shutter cannot be opened for more than 5 msec when imaging in the green. Therefore, the image recorded on the SSI camera will consist of a single bright pixel against the Earth background. Hence, the prime purpose of the descoped EGA1 GOPEX is to demonstrate the blind-pointing accuracy using the spacecraft ephemeris predictions and available guide stars and to demonstrate the reception quality of the uplink laser pulse by the spacecraft. The results from this demonstration can be used to determine the effect of uncertainties in the camera receiving optics; these effects can be as high as ±10 percent. They can also be used to calibrate the detection and propagation models and to predict performance for future experiments.

The full-up optical link performance will be demonstrated by EGA2 GOPEX, whereby the uplink laser will be pulsed at a faster rate so that successive data pulses can be recorded on a single image frame. The intensity of the laser signal recorded on the image can be checked against the threshold model developed during the EGA1 demonstration. This, in turn, determines the data pattern received by the spacecraft. During the EGA2 demonstration, approximately 200 image frames will be received from the spacecraft. Each image will record 10 data transmissions from the uplink laser. Since the bit error rate (BER) for the EGA2 GOPEX demonstration is anticipated to be on the order of 10^{-2}, the BER can be determined using the 2,000 data points and comparing the transmitted data with the received data. The experimental result can then be verified against the theoretical model.

The 2,000 data points collected during EGA2, however, will not be sufficient if the BER falls below 10^{-2}. If EGA1 GOPEX demonstrates better link quality than the prediction, the number of data points collected during EGA2 may have to be increased to determine the BER. Furthermore, increasing the number of data transmissions during the experiment will enhance the confidence level of the characterization of the optical link performance.

C. Demonstration Opportunities

The EGA1 GOPEX demonstration is scheduled to coincide with the Earth-spin movies that begin at ECA +2.5 days and end at ECA +3.5 days. SSI camera frames of the Earth will be taken every 6 min using all the SSI filters. The laser will be operated at the frequency-doubled green wavelength, and the transmission will be timed to coincide with the 5-msec opening of the camera shutter when the green filter is in place.

Although the details of the EGA2 demonstration are still undefined, the proposed full-up communications demonstration will benefit from the shutter opening times of hundreds of milliseconds that will allow for scanning the camera across the field of view of the Earth as the laser is pulsed. The GOPEX demonstration during the 1992 Earth flyby will occur between midnight and 6:00 A.M. Pacific Standard Time from 2 days to 4 days after ECA. The GOPEX demonstration conducted in this time frame will also benefit from the high data rate (28.8 kbps) communications between Galileo and the Deep Space Network (DSN).[1] During the periods of reduced communications data rate (7.6 kbps from ECA +4 days to ECA +14 days

[1] J. Ludwinski, *Earth Encounter Operating Strategy*, vol. IV, part V, JPL D-234 (internal document), Jet Propulsion Laboratory, Pasadena, California, January 1, 1988.

and 1.2 kbps from ECA +15 days to ECA +40 days), the demonstration will proceed less frequently depending on the availability of Galileo's tape recorder resource, which is a major consideration as to the frequency. After ECA +40 days, the spacecraft's attitude heading takes the Earth out of the field of view of the SSI camera, effectively terminating any opportunity to continue the GOPEX demonstration.

D. Laser Signal Strength at Galileo

The pulsed-laser signal strength W_{GII} (joules/square meter) in the far field at a distance z from the transmitter can be calculated using

$$W_{GII} = \frac{4W_t}{\pi(z\theta_t)^2}\,\eta_t\eta_{atm} \tag{1}$$

Here W_t is the transmitted laser pulse energy, θ_t is the full-angle beam divergence of the laser, z is the laser-to-SSI range, η_t is the laser's transmitting telescope optics efficiency, and η_{atm} is the atmospheric transmission efficiency.

Assuming an atmospheric limited-beam divergence of $\theta_t = 30$ μrad, and transmitting efficiencies $\eta_t = 0.59$, $\eta_{atm} = 0.57$ at 0.532 μm and 0.84 at 1.06 μm, the GOPEX laser signal strength at a range of 2×10^6 km is 1.83×10^{-11} J/m^2 at 0.532 μm and 13×10^{-11} J/m^2 at 1.06 μm.

The energy-per-pulse incident on a single pixel of the SSI camera W_{SSI} is calculated by multiplying Eq. (1) by the effective collection aperture of the camera A_c and the transmission efficiency of the camera optics η_r. This is given by

$$W_{SSI} = W_{GII}A_c\eta_r \tag{2}$$

For $A_c = 0.02$ m^2, $\eta_r = 0.2$ at 0.532 μm, and $\eta_r = 0.47$ at 1.06 μm, there are 2×10^5 and 6×10^6 photons incident on the CCD at 0.532 μm and 1.06 μm, respectively, at this value of minimum range. The maximum range for EGA1 will be 4×10^6 km, at which the laser intensities at the camera will be reduced by a factor of 4. During EGA2, the distance to the spacecraft can be much larger, thus further diluting the laser signal intensity. However, as noted earlier, the laser signal during EGA2 will be originating from a dark, rather than illuminated, Earth background.

E. Detection Probability Analysis (EGA1)

A basic model is used to analyze the detection probability of the GOPEX laser pulse. The model uses hypothesis testing to distinguish the absence or presence of the laser pulse in the presence of the bright Earth background. This section focuses on the trade-offs between a larger beam divergence to offset pointing errors and the concomitant decrease in the laser signal strength at Galileo.

To the SSI camera, the Earth is an extended source, and the number of photoelectrons per pixel received at the SSI camera is therefore independent of the spacecraft range. However, the laser appears as a point source, and the laser signal is imaged onto a single pixel. The strength of the laser signal at the CCD will decrease as R^{-2}, as the range R between the spacecraft and the transmitter station at TMO increases. Calculations of the earthshine for a 4.17-msec shutter opening of the SSI camera through the green filter show that approximately 60,000 photoelectrons/pixel are generated at the CCD by the Earth irradiance. Therefore, the signal detected by the CCD array is not dominated by laser shot noise.

Figure 4 plots the number of photoelectrons generated by the CCD, as a function of range, for laser beam divergences ranging from the atmosphere-limited divergence of 30 μrad to 70 μrad. A laser output of 0.25 J at 0.532 μm is used in these calculations. The results show that for atmosphere-limited beam divergence at a range of 2×10^6 km, the combined Earth and laser illumination exceeds the 10^5 photoelectron full-well capacity of the CCD. However, for laser beam divergences greater than 40 μrad, this combined illumination is less than the full-well capacity of the CCD array.

The detection probability results that follow are presented for beam divergences of 40–70 μrad and correspond to the case in which

(1) The laser illuminates a single pixel of the CCD detector. This reduces the planar detection problem to a point detection problem. The scenario of illumination at a pixel boundary is not considered at this time.

(2) The exact location of the pixel being illuminated is known a priori (that is, the location of TMO relative to the Earth image is known) and is tracked by a known algorithm.

(3) The detection threshold is based on analog-received signals. It is then quantized to one of the 256 levels.

(4) The saturation of the CCD well due to the combined laser pulse and the earthshine is declared as the presence of the GOPEX laser pulse.

(5) The standard deviation of the shot noise from the GOPEX laser pulse is considered to be small

compared with the earthshine. Consequently, the detector noise consists of the readout noise and the variance of the earthshine.

(6) The decision about the presence of the laser pulse is based on a single-frame observation.

Although the detection probability results presented here are for single-frame detections, the fact that frames are taken at 6-min intervals can be used to enhance the detection probability by seeking a bright pixel that moves over the Earth image 1.5 deg per frame.

Two hypotheses related to the basic model are defined as follows: When the GOPEX laser pulse is sent, it is called H_1, and when the laser pulse is not sent, it is called H_0. These two hypotheses give

$$\begin{aligned} H_1 : r &= \mu_s + e + n \\ H_0 : r &= e + n \end{aligned} \tag{3}$$

where r is the received signal represented in number of photoelectrons; μ_s is the known received number of photoelectrons due to GOPEX laser; e is a Gaussian random variable representing the number of received photoelectrons due to earthshine with mean μ_e and variance σ_e^2; and n is a Gaussian random variable representing the noise due to other disturbances with mean zero and variance σ_n^2.

Let P_{fa} be the probability of false alarm (that is, a laser is to be transmitted when it is not), and let P_d be the probability of detection (that is, a laser is said to be transmitted when it is). If $\Lambda(r)$ is the likelihood ratio of the two hypotheses, then

$$\Lambda(r) = \frac{\frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(r-\mu_s-\mu_e)^2}{2\sigma^2}}}{\frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(r-\mu_e)^2}{2\sigma^2}}} \tag{4}$$

where

$$\sigma^2 = \sigma_e^2 + \sigma_n^2$$

Under the Neyman–Pearson criterion, the probability of detection can be maximized by setting the detection threshold to the likelihood ratio for a given probability of false alarm. Equation (4) gives

$$ln\Lambda(r) = \eta \tag{5}$$

or

$$\frac{r}{\sigma} = \frac{\mu_e}{\sigma} + \frac{1}{2}\frac{\mu_s}{\sigma} + \frac{ln\eta}{\frac{\mu_s}{\sigma}} \tag{6}$$

When the number of received photoelectrons normalized by the standard deviation σ exceeds the right-hand side of Eq. (6), the GOPEX laser pulse is declared present. Since the CCD readout is digitized to 256 levels, the detection threshold must be quantized to one of the 256 levels. Therefore, the maximum $\frac{r}{\sigma}$ that can be achieved at any time is 256. The detection threshold is given by

$$r_{\text{det}} = \lceil (r/\delta) \tag{7}$$

where $\lceil (x)$ is the smallest integer that is larger than x, and δ is the number of photoelectrons represented by each unit of CCD readout. Then

$$P_{fa} = \frac{1}{2}\text{erfc}\left\{ \frac{1}{\sqrt{2}} \left[\frac{r_{\text{det}} * \delta}{\sigma} - \frac{\mu_e}{\sigma} \right] \right\} \tag{8}$$

$$P_d = \frac{1}{2}\text{erfc}\left\{ \frac{1}{\sqrt{2}} \left[\frac{r_{\text{det}} * \delta}{\sigma} - \frac{\mu_e}{\sigma} - \frac{\mu_s}{\sigma} \right] \right\} \tag{9}$$

where erfc $(\cdot)$ is the complementary error function given by

$$\text{erfc}(x) = \frac{2}{\sqrt{\pi}} \int_x^\infty e^{-t^2} dt$$

Therefore, for any given probability of false alarm, the detection threshold can be computed using Eq. (8), and the resulting threshold will be quantized to one of the 256 levels.

Figures 5, 6, and 7 show some of the computation results for the 0.532-μm laser. Without loss of generality, the probability of false alarm is taken to be no more than 1 percent. The noise variance due to CCD readout is extracted from [3]. Figure 5 plots the probability of detection as a function of the beamwidth of the GOPEX laser pulse when the spacecraft is 4 million km away from the Earth. The standard deviation σ_e of the earthshine is taken to be 1,000 photoelectrons. The curves are parameterized by the pointing errors of 10, 20, and 30 μrad. When the pointing error is large compared with the beamwidth, the probability of detecting the presence of the GOPEX laser pulse degenerates to the probability of searching the GOPEX laser pulse within the additional space spanned by the pointing error. Consequently, the probability of detection decreases to zero as the beamwidth is reduced. On the other hand, since the intensity of the GOPEX laser pulse is reduced with widening beamwidth, the detection probability will decrease with increasing beamwidth. It can be seen that for all three cases, the maximum detection probability is achieved when the beamwidth is between 30 to 50 μrad.

Figure 6 shows the probability of detection when the spacecraft is the same distance away from the Earth with no pointing error and parameterized by the standard deviation of earthshine σ_e. Figure 7 shows the probability of detection as a function of distance of the spacecraft in million of kilometers for beamwidths of 40, 50, 60, and 70 μrad. The cases of $\sigma_e = 2{,}000$ are represented by dark lines, and the cases of $\sigma_e = 4{,}000$ by light lines.

These figures indicate that if the pointing error of the GOPEX laser pulse is confined to less than 30 μrad, the beamwidth should be maintained between 30 to 50 μrad to maximize the detection probability. Furthermore, the detection probability is marginal when the spacecraft is 4 million km away from the Earth. Multiple-frame detection should be used to increase the detection probability.

F. Precursor Demonstrations

The LACE (low-power atmospheric compensation experiment) satellite illumination and Lageos (Laser Geodynamics Satellite) ranging experiments are proposed as precursors to the GOPEX demonstration. There are three fundamental objectives of these experiments:

(1) They will be used to evaluate theoretical predictions of laser beam propagation through the atmosphere.

(2) They will provide an opportunity to test and calibrate the ground transmitter system.

(3) They will allow the GOPEX experimenters opportunities to become skilled in communicating with a spaceborne target.

One of the functions of the Strategic Defense Initiative Office (SDIO)/LACE satellite is to measure the absolute intensity of laser beams transmitted from the ground. The LACE satellite is in orbit around the Earth at a height of 547 km and at an inclination of 43 deg. For the JPL/LACE illumination experiment, the pulsed-array sensor on board the spacecraft will be used to detect the 1.06-μm laser beam. This sensor consists of a 38 × 50-in. array of 85 silicon detectors located on board the satellite. The sampling cycle of the pulsed sensor is of 100-msec duration with 2.06-msec sampling windows at 10-msec intervals and supports signal detection for a maximum laser-pulse repetition rate of 10 Hz. In the pulse repetition mode, the GOPEX laser is capable of firing at 6, 15, and 30 Hz, respectively. The 6-Hz laser repetition rate is chosen for the JPL/LACE illumination experiment in order to ensure that the satellite receives only a single laser pulse during each sampling cycle. The detected signals are stored on board the satellite until downlinked via S-band (2.29-GHz) radio frequency to the transportable ground station (TGS) located at Vandenberg Air Force Base or White Sands Missile Range. The data will then be analyzed to characterize the laser beam intensity, beam spread, and distortion at the top of the atmosphere.

Lageos is a passive, Earth-orbiting satellite in the form of a 60-cm ball and is uniformly covered with retroreflectors. Lageos orbits at a height of 5900 km and is inclined at 110 deg. The transmitted laser beam will be retroreflected by the satellite and detected at the ground transmission station at TMO. The laser beam's round-trip time between the ground station and Lageos is approximately 40 msec. Although this will support a maximum repetition rate of 25 Hz without interleaving the transmit and receive pulses, the selectable pulse repetition rates of the laser dictate a repetition rate of 15 Hz for the Lageos ranging experiment. The immediate signal return of the Lageos experiment will allow rapid evaluation of the telescope pointing capabilities of the system and will permit a ready comparison of experiment results with theoretical predictions.

III. Preparation Activities

In addition to the administrative activities, preparation activities for the GOPEX demonstration during the first Earth flyby include identification and calculation of the impact of the various error sources such as optical propagation losses and pointing errors that would affect the quality of the optical uplink to Galileo. In Section II, the effect of pointing error on the detection probability was discussed. In that calculation, the pointing error was treated as an aggregate of several error sources, each contributing to the net error, which was used in the analysis.

Among the preparation activities for GOPEX, the design of the optical system is an item that is critical to minimizing the pointing error. The principal objectives of the design are to ensure the overlap between the outgoing laser beam propagation direction and the optic axis of the telescope and to allow the divergence of the laser beam to be varied continuously to ensure optimal beam divergence for the precursor experiments. The optical system described in Section III.A is a preliminary design intended to achieve a 5-μrad overlap between the telescope axis and the outgoing laser beam and will allow for easy adjustment of the divergence of the laser beam.

A. Experiment Description

Figure 8 is a schematic of the laser/telescope arrangement. The output from the Nd:YAG laser first passes through a telescope T1 of magnification M = 1. T1 consists of two 10-cm-focal-length achromats and a highly polished 100-μm reflecting surface pinhole with the aperture drilled at a 45-deg angle of incidence. The laser beam is focused on the pinhole, which is used to facilitate the coalignment of the transmitted laser beam with the optic axis of the telescope. The pinhole is placed in an evacuated chamber with optically transparent windows to prevent ionization of the air caused by the intense optical fields at the focus of the T1 telescope's short focal length lenses. The laser beam emitted from T1 by the beam expander T2 is expanded to a 50-mm-beam diameter. The expanded laser output of T2 is then coupled through a diverging lens NL1 for mode match to the 24-in. astronomical telescope through a coudé mount arrangement.

Coalignment of the laser beam direction with the optical axis of the 24-in. telescope is accomplished by placing the pinhole in telescope T1 into the optical train so that the image of a distant star is brought into alignment with the pinhole. In the alignment procedure, the unfocused image of the star is reflected off the highly polished reflecting surface of the pinhole, and the focus of the astronomical telescope is adjusted until the image is brought into focus and then disappears through the pinhole. The image of the star on the pinhole can be viewed through the eyepiece E1 shown in Fig. 8. It is estimated that using this method, coalignment accuracies to within 5 μrad can be achieved with a 100-μm pinhole.

In Fig. 8, Block L1 is the signal detection arrangement for the Lageos precursor experiment. The optical return from Lageos is collected by the 24-in. telescope and is returned through the optical train shown in this figure. The 50/50 nonpolarizing beam splitter B1 reflects 50 percent of the return signal to the lens LL1, which focuses it onto the avalanche photodiode detector (APD) D1. The 1-nm-bandwidth interference filter F1 positioned in front of the APD reduces the photons count from other celestial bodies, which are within the field of view of the telescope. The flag FF1 is positioned directly in front of the detector and protects the detector from reflections of the high-intensity transmit pulse at surfaces along the optical train. The flag remains positioned in front of the APD for a few milliseconds—after the laser pulse is emitted—and then swings out of the beam path to allow the retroreflected beam from Lageos to be detected. After a delay time corresponding to the laser pulse's round-trip time and prior to the emission of the next laser pulse, the flag swings back in front of the detector to once again protect it from spurious reflections of the high-intensity outgoing radiation.

The optical power transmitted to the astronomical telescope is monitored by the silicon detector S1, which measures the reflection from the thin, uncoated glass disc GD1 shown in Fig. 8. The laser reflection from GD1 is calibrated to the power transmitted through GD1, where the measured signal power is stored in a computer file.

B. Telescope Upgrade

JPL's Earth and Space Sciences Division is responsible for the telescope upgrade activities. This group has purchased the requisite hardware and, with the assistance of JPL's Robotics and Automation Systems Section, is preparing a telescope-control software package to provide the telescope pointing and control necessary for the GOPEX demonstration.

The GOPEX deliverables from this telescope upgrade activity include a computer-controlled 24-in. telescope with a pointing accuracy of 5 μrad and software that can take spacecraft ephemeris inputs and the true and apparent guide star positions inputs and then use them to generate a file with the corrected position for pointing the telescope to Galileo. This method of compensating for the effects of telescope flexure and atmospheric refraction obviates the need for performing a time-consuming and only marginally useful mount calibration of the telescope to compensate for flexure and reduce errors in pointing resulting from atmospheric refraction. The compensated data, consisting of the corrected telescope-pointing positions for Galileo, will be used as inputs to point the telescope to the spacecraft during the GOPEX demonstration.

C. Laser Installation

The GOPEX laser is a Nd:YAG model YG581-30SHG made by Quantel. The laser was transported to TMO in May 1990 and was installed in the coudé room of the 24-in. telescope observatory. All electrical connections were completed: 208 VAC; 3-phase, 30 amps/phase for the laser power supply; and 208 VAC single phase for the cooler. The laser was fully operational by mid-July 1990.

The heat generated by the laser power supply and cooler would normally be vented into the coudé room. However, it was felt that during laser operation the amount of heat that would be vented into the well-insulated coudé room would duct its way up to the telescope floor and degrade the seeing conditions at the telescope. To avert potential problems, a means of venting the heat from the coudé room to the outside was constructed. Care was taken to ensure that the vented air would not interfere with the seeing conditions of the telescope.

D. Federal Aviation Administration, Laser Clearing House, and JPL Occupational Safety Office Safety Procedures

The Federal Aviation Administration (FAA) has responsibility for ensuring the safety of air traffic and, therefore, has jurisdiction over the propagation of laser beams transmitted through the atmosphere. Although the laser is not powerful enough to damage an aircraft, the laser pulse can be blinding to anyone looking into the beam. To ensure the safety of aircraft pilots and passengers, the FAA will issue a Notice to Airmen (NOTAM) to restrict the airspace around TMO during the precursor experiments.

During the EGA1 GOPEX demonstration, the safety procedure will be modified to accommodate the low-elevation laser beam transmission to Galileo. Line of sight from TMO to Galileo during EGA1 crosses the aircraft approach path to the Los Angeles International Airport (LAX) with the spacecraft rising in the southern sky shortly before sunrise. The laser beam avoidance procedure will allow FAA personnel to space aircraft transits across the line of sight to Galileo so that such transits do not coincide with the approximate 100 msec of laser transmissions every 6 min. The proposed procedure for the Galileo demonstration is to contact a designated LAX air traffic controller and request a check for aircraft crossing a predetermined beam path. A spotter looking through a sighting scope coaligned with the 24-in. telescope will visually check for aircraft in the vicinity of the beam path. Should either the air traffic controller or the spotter confirm the presence of an aircraft within the previously agreed upon angular distance from the beam path, laser transmission will be inhibited. The air traffic controller will be in telephone contact with the GOPEX operator who can interrupt laser transmission, if necessary.

The Laser Clearinghouse, under the United States Space Command headquartered at Peterson Air Force Base, has responsibility for monitoring Earth-orbiting objects and spacecraft and also for determining whether a spaceborne object could be interfered with, degraded, or damaged by a laser. Since illuminating a U.S. satellite with a laser beam could potentially be a national security issue, the GOPEX team will work with the Laser Clearinghouse to ensure that laser transmission will not occur should it pose a threat to sensitive satellites. The GOPEX team will provide laser transmission vectors to the Laser Clearinghouse, which will determine whether or not an object that should not be illuminated will pass within 3.5 deg of the laser beam vector. If such is the case, the Laser Clearinghouse will notify the GOPEX team not to transmit the laser beam at that time.

The Occupational Safety Office at JPL is responsible for ensuring that safety practices are followed while the laser is operated. The GOPEX team has completed the Operational Safety Review form JPL 0284-S, which outlines the steps that will be taken to ensure the laser is operated in a safe manner with no impact on the environment. The form has been submitted to the Occupational Safety Office. The review procedure requires a representative from the Occupational Safety Office to evaluate and sign off the safety procedures that will be followed.

E. Navigation Systems Ephemerides

TMO, the ground station location for GOPEX, is located at 34.382° north latitude, 242.32° east longitude, at an altitude of 2284 m. The EGA1 GOPEX demonstration that will be carried out during ECA +2.5 and ECA +3.5 days will benefit from several days of post-encounter radio metric tracking, and as a result the ephemerides for Galileo will be good to approximately 0.5 μrad. JPL's Navigation Systems Section will generate an ephemeris file for Galileo relative to TMO's location for those times that the demonstration will be conducted.

The calculated ephemerides will be transferred as a data file to a terminal at TMO via the JPL electronic mail system. This data file will be the input data file to the telescope-pointing software to generate the corrected coordinates for pointing the telescope toward Galileo.

F. Data Collection and Analysis

The differences between the data collection and data analysis methods used in the LACE and Lageos precursor experiments and those used in the GOPEX demonstration reflect differences in the capabilities of the spacecraft targets. SDIO/LACE is essentially a large optical targetboard in the sky and is capable of measuring laser beam intensity distributions and laser beam distortions that result from atmospheric effects. These types of data from the SDIO/LACE satellite will, at best, take several hours to retrieve and analyze. In contrast, the data returned from the retroreflecting Lageos satellite are immediate, and the strength of the signal returns from this satellite is a measure of the pointing accuracy of the transmitter. The data from the GOPEX demonstration are the output from the SSI camera on Galileo, which will be in the form of 8-bit resolution data numbers. It is not anticipated that these data will be retrieved and analyzed within the 25-hr window of the EGA1 demonstration.

In the JPL/LACE experiment the data from the satellite will be downlinked to the TGS, and then routed to the experiment data processing center. The data will then be formatted so that they are compatible with the sensor array subsystem display program (SASDISP). As a part of the definition phase of the JPL/LACE experiment, a copy of this program was supplied to the GOPEX team by the Bendix Field Service contact responsible for defining experiments on SDIO/LACE. After the data are formatted, they will then be sent via computer mail to the GOPEX team at JPL for analysis. The SASDISP will allow the GOPEX team to analyze the satellite data and to correlate the propagated laser intensity, the beam spread, and distortion with the local atmospheric conditions such as temperature, humidity, and pressure at the TMO transmitter site.

Data collection for the Lageos ranging experiment will be done at the transmit/receive site. The return signal detected by the APD detector will be displayed on a LeCroy 9450 digital oscilloscope. An 80386-based computer will be used to control the oscilloscope and to store the received signal intensities as a function of time. The pre-trigger and post-trigger recording feature of the LeCroy will be used to define a window within which the return pulse should arrive.

The post-trigger recording is powerful enough to allow data to be acquired only where an interesting return signal occurs. For the Lageos experiment, the repetition rate of the laser is 15 Hz, meaning that the 10-nsec laser pulse is transmitted every 67 msec. Assuming the return signal is of a similar form, this results in 10 nsec of useful data every 67 msec. This implies that more than 66.9 msec of every 67 msec consists of meaningless information. If the digital oscilloscope delays its recording time until the return signal occurs, a higher bandwidth of the meaningful signal can be recorded. To optimize the bandwidth of the recorded return signal for the Lageos ranging experiment, the transmitted laser pulse will serve as the trigger and the time delay for post-trigger recording will be set for approximately 38 msec, slightly less than the 40-msec round-trip time of the laser pulse between the ground station and Lageos.

If the laser pulse hits the target, the retroreflected signal will occur within the time window. The retroreflected signal intensities will be compared with theoretical predictions, and the time delays of the return signals will be used to determine the satellite's range from TMO. The frequency of the return signal will allow the overall statistical probability of hitting the satellite under various atmospheric conditions to be determined. These data will help determine the pointing accuracy of the transmitter system and will be used to improve the atmospheric propagation models used for the GOPEX demonstration.

For the GOPEX demonstration, the camera images of the laser transmission will be downlinked to JPL's DSN facilities via an 8.5-GHz signal. The SPICE kernel concept will be used to generate a data record consisting of various types of ancillary information on the spacecraft at the time of the experiment. The GOPEX team is mostly interested in the I and C kernels. The I kernel provides information on the instrument alignment and the C kernel information on the spacecraft and scan platform pointing [4]. This information along with the results of the camera frame will facilitate the correlation of the laser transmit times with the shutter opening times and the scan platform pointing. A list of the 6 bits of information in the SPICE kernel data base is listed below.

Kernel	Description
S	Spacecraft trajectory
Pe	Planet or satellite ephemerides
Pc	Planet/satellite physical constants
I	Instrument alignment information
C	Spacecraft and scan platform pointing information
E	Sequence of events

Information from the experiment data record and the ancillary data in the SPICE kernels will be processed at the appropriate home institution image processing system (HIIPS) site. There are 12 such sites for processing SSI data from Galileo. Ten sites are located in the United States in addition to one in Canada and one in Germany. Seven sites are located in the Western United States: three in California (two at the United States Geologic Survey in Menlo Park and one at the Rand Corporation in Santa Monica) and four in Arizona. The GOPEX team will work with the HIIPS at the site chosen by the SSI team.

IV. Coordination With Galileo Project Office

As the Galileo Project Office continues to define the science activities that will be included in the Earth-encounter sequence for the 1990 Earth flyby, the opportunities for GOPEX continue to be defined. Coordination with Galileo

Project Management, the SSI team, and the Galileo SROP (Science Requirements and Operations Planning) team has resulted in opportunities for the GOPEX demonstration to coincide with the Earth-spin movie activities from ECA +2.5 days to ECA +3.5 days.

Currently, the issues to be resolved by the Galileo Project Office before official concurrence is given for the GOPEX demonstration are those of safety of the SSI camera and the effect of the laser pulse on the other sensors on board Galileo. With respect to the spacecraft systems in general, it has been shown that for the laser power levels at Galileo, the laser beam in no way jeopardizes any of the spacecraft systems. The impact of the laser signal on other sensors on Galileo is now being considered by JPL's Observational Systems Division personnel. In addition, the principal investigators of the near infrared mapping spectrometer, the photopolarimeter, and the ultraviolet and extreme ultraviolet spectrometers, the four optical science instruments on board Galileo, are studying the impact of the laser signal on their detectors.

V. Challenges

There are several challenges to a successful GOPEX demonstration:

(1) The possibility of cloud cover over TMO during the 25-hr period during EGA1 when the demonstration is scheduled.

(2) The ability to accurately point the telescope to the spacecraft while compensating for atmosphere refraction.

(3) The ability to time the laser emission to ensure that the signal arrives at Galileo when the camera shutter is open and the green filter is in place.

A. Cloud Cover

Although the weather patterns over the past several years indicate a low probability of cloud cover and precipitation during the month of December at TMO, anomalies in weather patterns are not uncommon and can jeopardize the success of the GOPEX demonstration. Since the demonstration at EGA1 is considered a best-effort demonstration (due to poor viewing geometry and background lighting conditions), no special cloud-cover work-around strategies are planned. However, for the primary GOPEX demonstration at EGA2, uplink spatial diversity will be considered as a means of achieving the demonstration goals.

B. Telescope Pointing Accuracy

Factors that contribute to the telescope pointing errors and that affect the propagation direction of the laser beam include beam wander, atmospheric refraction, laser beam misalignment with the telescope axis, and mechanical vibrations of the telescope and other optical components. Although some of these effects are minimal, combined they can result in a large pointing error and impact the probability of illuminating Galileo with the optical signal.

Of all the factors contributing to telescope pointing errors, it is believed that the effect of refraction is the major single contributing factor. This is especially true for the EGA1 demonstration when Galileo remains low in the sky. In Section V.C the effects of refraction are discussed. This discussion is followed by a description of a method of using guide stars in the vicinity of Galileo to mitigate the effects of off-pointing caused by refraction and telescope flexure.

C. Atmospheric Refraction

Because of the high accuracy required for the pointing of the laser signal from TMO to Galileo, compensation for atmospheric refraction is essential. Near the horizon, the refraction can be as large as 10 mrad. Figure 9 shows the temperature dependence of the magnitude of the refraction for 1.06 μm at a zenith angle of 60 deg for a simple flat-Earth model. (The refraction is about 1.5 percent greater at 0.532 μm.)

Most atmospheric refraction models are not valid to better than about 20 μrad [5], so measurements will have to be made during the demonstration to supplement the calculations. By observing a star of known position near Galileo, the telescope pointing can be calibrated, thus permitting a large part of the atmosphere-induced error to be overcome. Yet, the closest reference star identified will still be over 1 deg from Galileo [6], and when the zenith angle is changed by less than 1 deg, the predicted refraction can change by over 10 μrad. Thus, to aid in deriving the refraction at Galileo, it will be important to combine a measurement of the refraction at the location of the reference star at the time of the demonstration with a model. This measurement will provide a data point for input into the atmospheric correction model. It is estimated that for a data point sufficiently close to Galileo, the error in the modeled atmospheric compensation correction will be small.

D. Guide Stars for Locating Galileo

During the window of opportunity for GOPEX, the spacecraft position will be in the vicinity of 14 hr 40 min right ascension and 33 deg 45 min declination. A guide star, to be used as an accurate pointing reference, has been identified 1.6 deg away at 14 hr 43 min 39 sec right ascension and -35 deg 10 min 23 sec declination. This star, designated HD129456, has a visual magnitude of 4.05 and is red, indicating that it may be seen against the blue morning sky with appropriate optical filtering. Calculations and experiments are under way to determine the optimum method of locating this star during the time of the GOPEX demonstration.

If it is visible, another nearby star may prove useful for calibrating the atmospheric refraction and telescope flexure. Located only 0.27 deg from the primary reference star identified above is the star HD129685, a white star of visual magnitude 4.92. If it can be located against the bright sky, the measurement of the apparent angular separation of these two stars could permit a very accurate calibration of the pointing errors. This would enable pointing to Galileo using an offset from one of the two stars, rather than trying to bring the telescope directly to the corrected absolute coordinates of Galileo.

E. Timing of Laser Emission

The GOPEX pulse must be received by the spacecraft within the shutter opening time of the SSI camera. Both the spacecraft and the GOPEX laser receive the WWVB clock for synchronization. Because of the uncertainty of the WWVB clock, the worst scenario occurs when the clock received at the GOPEX laser is slower than that indicated by the WWVB clock, and the clock received by the spacecraft is ahead of the time indicated by the WWVB clock. Other uncertainties being considered are the camera shutter open uncertainty of ± 1 msec, spacecraft location uncertainty of ± 10 km (0.3 msec), time delay between the fire signal and the fire-Q switch signal of 0.25 msec, and the width of the GOPEX laser pulse of 10 nsec. Figure 10 shows the timing diagram that includes these uncertainties. The top axis shows the control signals for the GOPEX laser. The middle axis shows the timing at the transmitter while the bottom axis shows the timing at the spacecraft.

In Figure 10 the GOPEX laser is assumed to be precharged for at least 33 msec before reaching the time zero mark. Likewise, the time of flight of the pulse varying between 3.333 sec (1 million km) and 13.333 sec (4 million km) is also assumed to be available to the spacecraft. The camera shutter opens for $4\frac{1}{6}$ msec to wait for the GOPEX laser. It is clear that with all these uncertainties, there is approximately 0.5-msec guard time between the reception of the laser pulse and the closing of the camera shutter.

VI. Conclusion

This article describes the GOPEX uplink optical communications demonstration. This demonstration, which is part of JPL's plans for the development of its deep-space optical communications capabilities, will use a Nd:YAG laser coupled to the 24-in. astronomical telescope at TMO as an optical transmitter to demonstrate deep-space optical communications with a spacecraft in flight.

GOPEX is scheduled to occur in December 1990 and again in December 1992, during the Earth-encounter phases of the Galileo spacecraft's trajectory. In addition to successfully meeting the technical challenges of this first demonstration of deep-space optical communications, a successful GOPEX demonstration will reflect the coordination and support of several JPL divisions and federal agencies. The Earth and Space Sciences Division is responsible for upgrading the 24-in. telescope at TMO so the desired telescope pointing accuracy can be obtained. The studies by the Observational Systems Division will provide assurances to the Galileo Project Office that there are no risks to the space science instruments on board the spacecraft. The FAA Los Angeles Central Office in Palmdale, California, and the Laser Clearinghouse at Cheyenne Mountain, Colorado, are the two federal agencies with which aircraft and sensitive satellite avoidance strategies have been worked out. These avoidance strategies are being implemented in the months preceding GOPEX, during the transmitter evaluation and precursor demonstration phases of the project.

References

[1] J. R. Lesh, L. J. Deutsch, and W. J. Weber, "A Plan for the Development and Demonstration of Optical Communications for Deep Space," *TDA Progress Report 42-103* (this issue), vol. July–September 1990, Jet Propulsion Laboratory, Pasadena, California, pp. 97–109, November 15, 1990.

[2] T. C. Clarke, "Earth and Moon Encounters by the Galileo Jupiter Orbiter," *The 1988 International Geoscience and Remote Sensing Symposium (IGARSS): Moving Towards the 21st Century*, vol. 3, European Space Agency Publication, pp. 1841–1844, 1988.

[3] K. Klaasen, M. Clary, and J. Janesick, "Charge-Coupled Device Television Camera for NASA's Galileo Mission to Jupiter," *Optical Engineering*, vol. 23, no. 3, pp. 334–342, May/June 1984.

[4] C. Acton, "The Space Concept: An Approach to Providing Geometric and Other Ancillary Information Needed for Interpretation of Data Returned From Space Science Instruments," paper presented at the AIAA/NASA 2nd International Symposium on Space Information Systems, Pasadena, California, September 19, 1990.

[5] J. A. Behuncik, *Tropospheric Refraction Corrections as Applied to MSFN Measurements*, Publication X-832-70-101, Goddard Space Flight Center, Greenbelt, Maryland, April 1970.

[6] M. D. Rayman, "Selection and Observability Tests of GOPEX Reference Stars," *TDA Progress Report 42-103* (this issue), vol. July–September 1990, Jet Propulsion Laboratory, Pasadena, California, pp. 278–283, November 15, 1990.

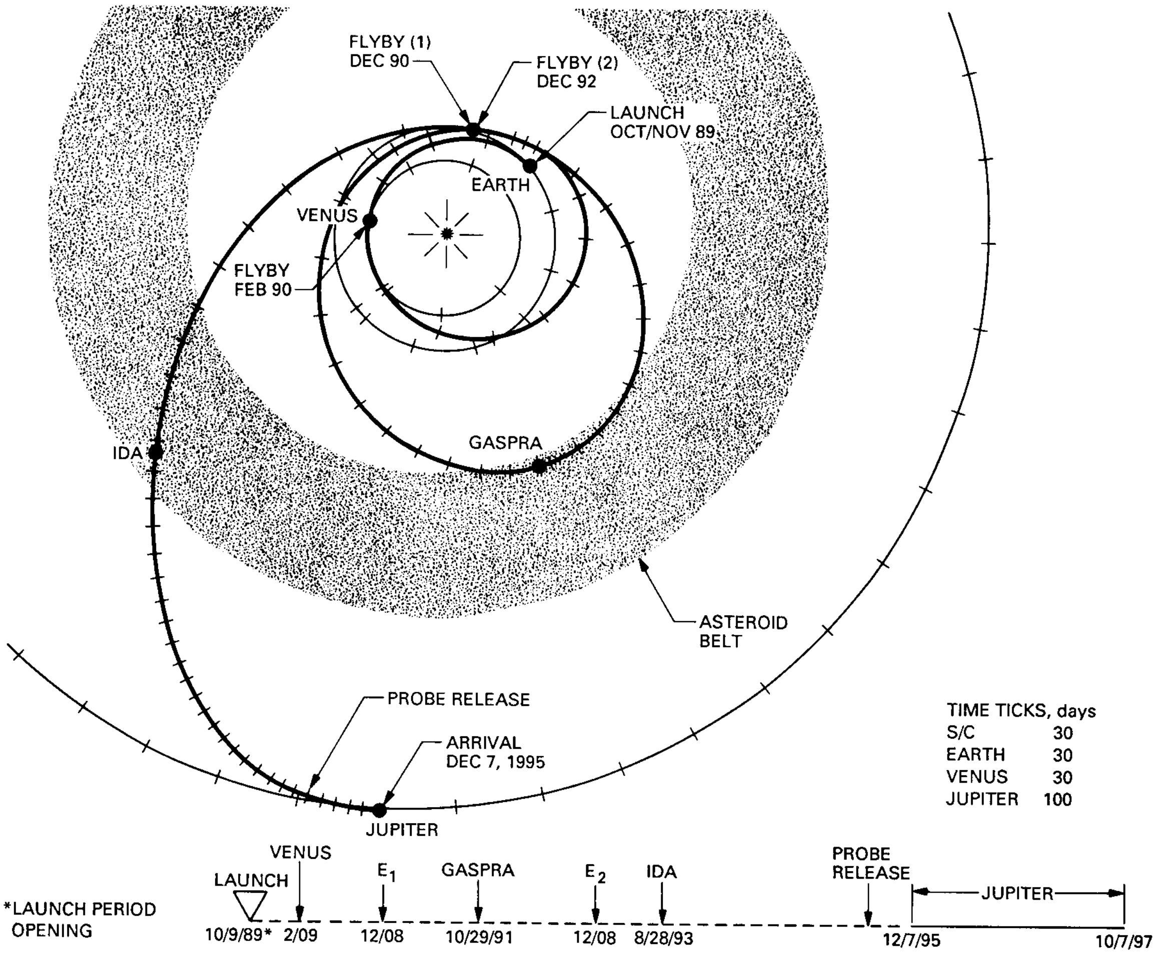

Fig. 1. VEEGA trajectory of Galileo.

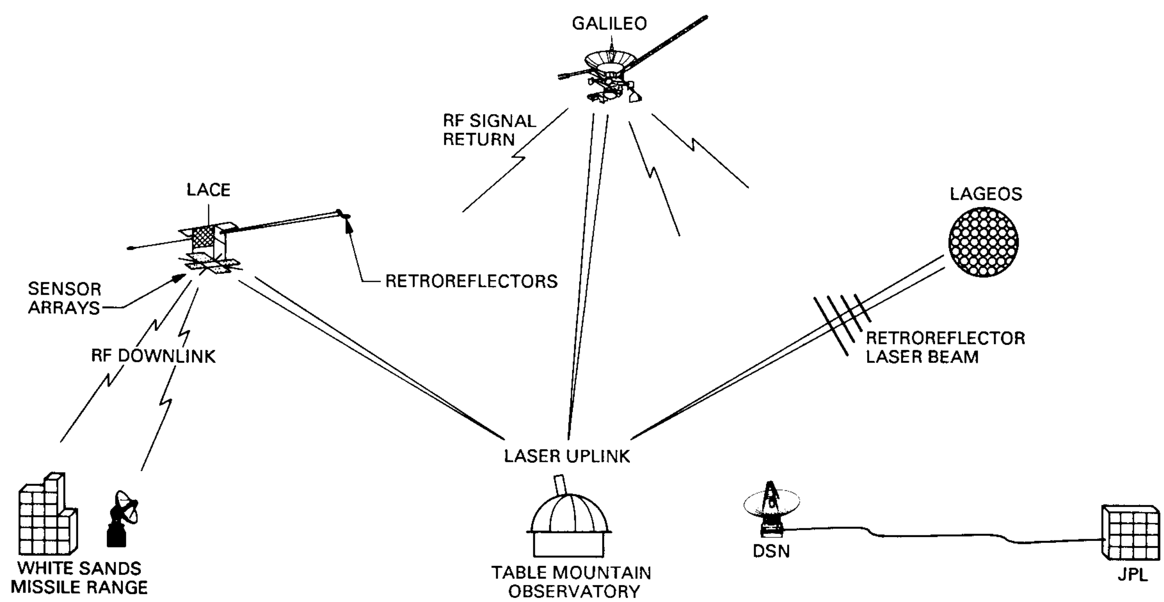

Fig. 2. GOPEX uplink to Galileo spacecraft.

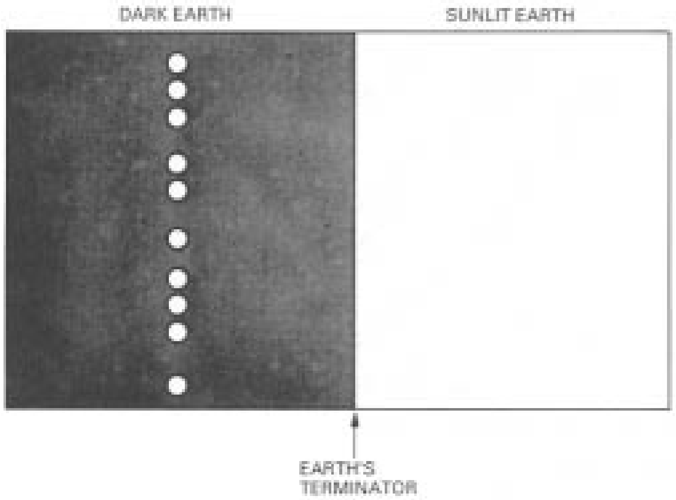

Fig. 3. Camera frame showing the transmitted laser signal against the dark Earth background. The temporal modulation of the laser is converted to a spatial modulation at the CCD by scanning the camera across the image of the Earth.

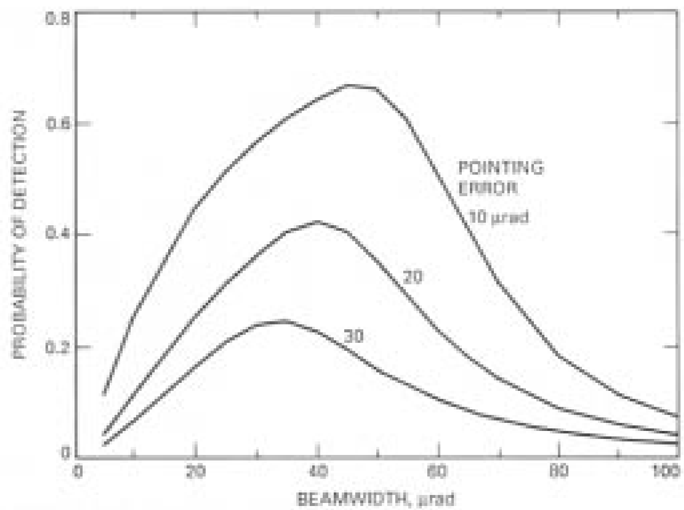

Fig. 5. Degradation of the detection probability due to laser-pointing errors. (Distance: 4 million km; $P_{fa} \leq 1$ percent; standard deviation of earthshine; 1,000 photoelectrons.)

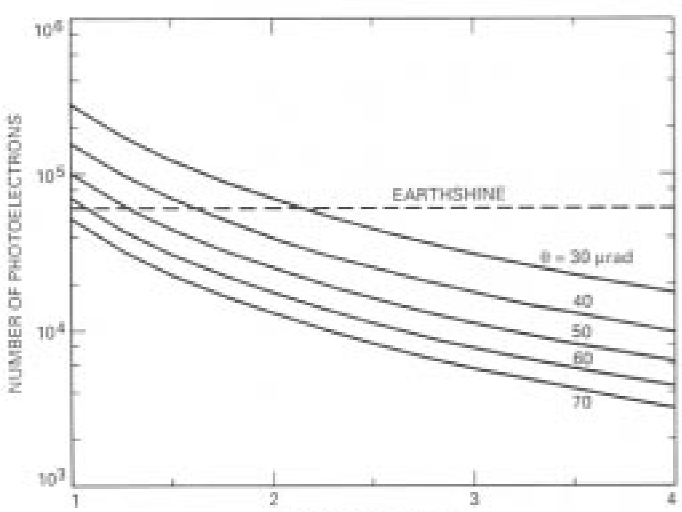

Fig. 4. Comparison between the number of photoelectrons by earthshine and the GOPEX laser pulse. (GOPEX laser source: 0.25 mJ; 0.532 μm.)

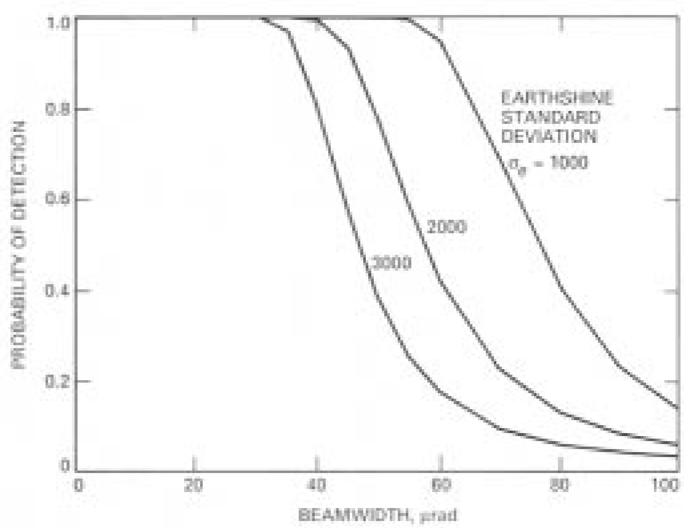

Fig. 6. The penalty of increasing laser beamwidth for the detection probability. (Distance: 4 million km; $P_{fa} \leq 1$ percent; $\mu m = 60{,}298$ photoelectrons.)

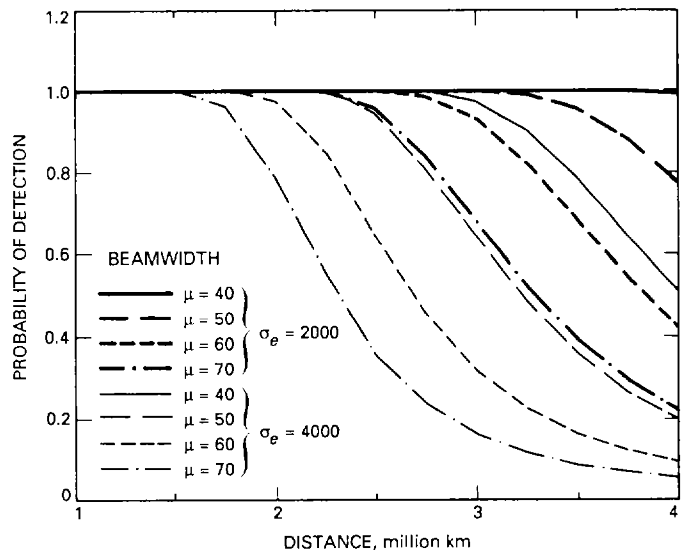

Fig. 7. The decrease in detection probability due to increasing distance of spacecraft from Earth. (No pointing error; $P_{fa} \leq 1$ percent; $\mu_e = 60{,}298$ photoelectrons.)

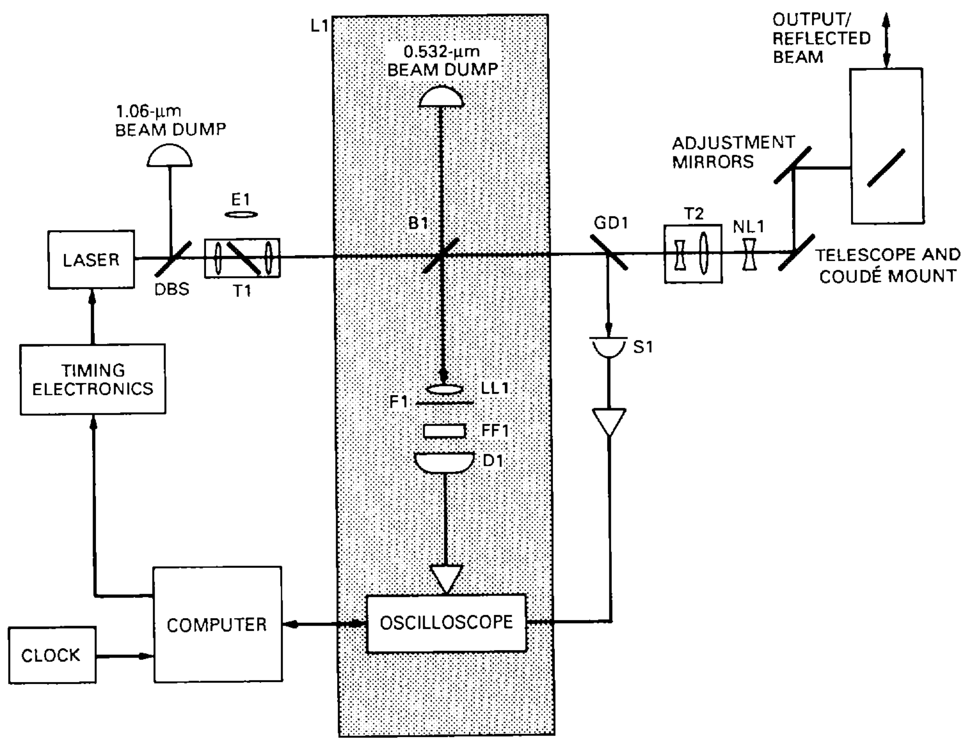

Fig. 8. Laser transmitter optics design.

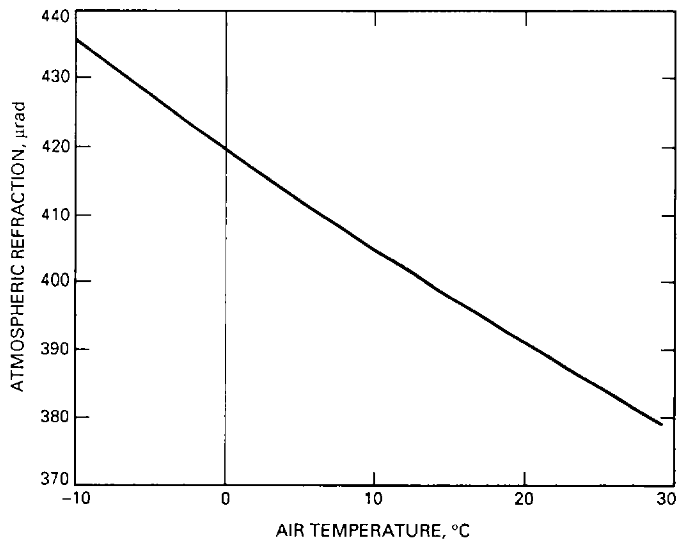

Fig. 9. Temperature dependence for a flat-Earth model.

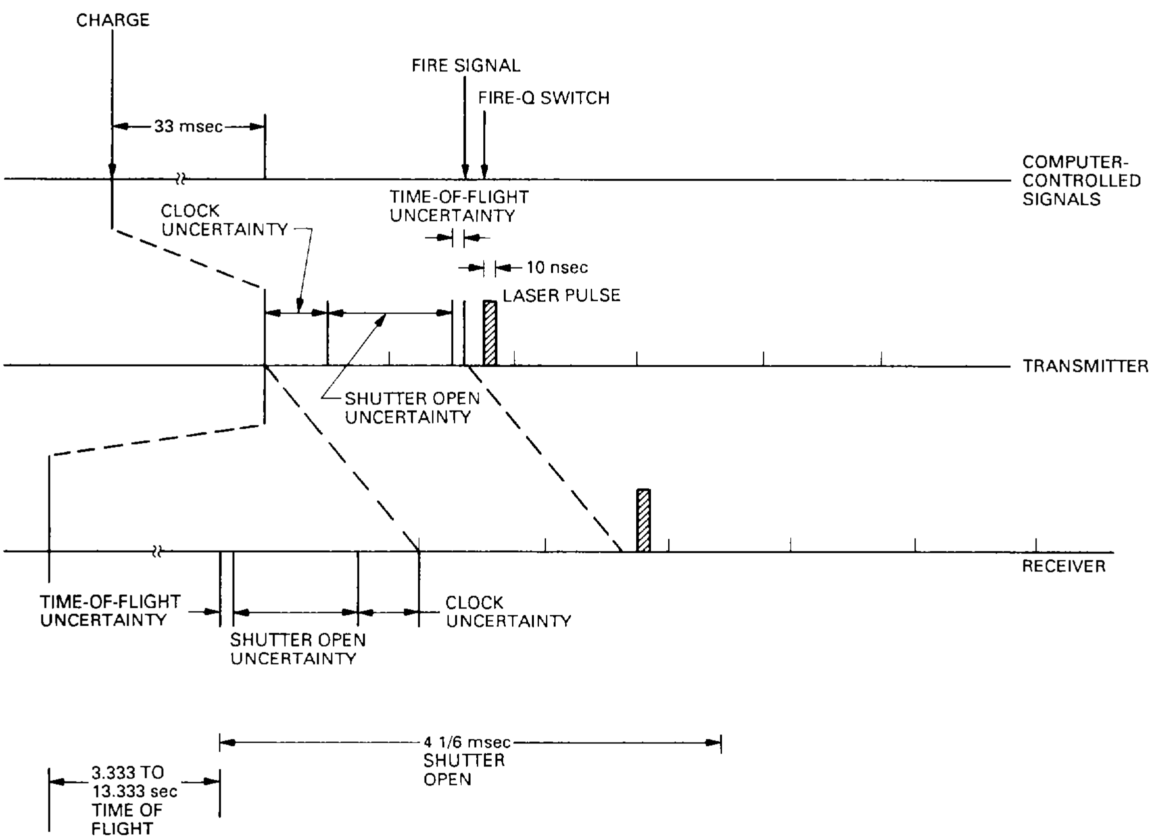

Fig. 10. Timing diagram of a GOPEX pulse.